Japan's First Operation of High-Temperature Superconducting Cable Systems in Live Grids (High-Temperature Superconducting Cable Demonstration Project)

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Sumitomo Electric Industries, Ltd. has taken part in the high-temperature superconducting (HTS) cable demonstration project, began in 2007, to verify the reliability and operational stability of HTS cable systems in actual power grids. The company has developed 66-kV-, 200-MVA-class HTS cables, terminations and joints, and built a 30-meter cable system using them to conduct verification tests before the demonstration in Tokyo Electric Power Company's Asahi Substation in Yokohama. At present, Phase I of the rating validation test has been completed with favorable results, verifying the soundness of the 30-m cable system. A 30-day long-term operation test was also completed successfully. Going forward, Sumitomo Electric will conduct heat cycle and marginal performance tests with the system in Phase II and Phase III.

Keywords: high temperature superconductors,superconducting cables,power cable installation

1. Introduction

The reduction of CO_2 emissions to combat global warming is one of the most pressing issues in the electric power business; however, the fact is that no measures are currently available that would effectively reduce electric power transmission and distribution losses, which currently hover around 5%. Likewise, the replacement of large-capacity pipe-type oil-filled cables (POF cables), which are becoming obsolete, is expected to go into full swing sometime around 2016. Replacing them with low-capacity cross-linked polyethylene vinyl sheath cables (CV cables), however, requires additional circuits, which is rather impractical due to the difficulties inherent in constructing new cable tunnels in urban districts.

Because they fit large-capacity, low-loss power transmission hardware into a compact package [1], high-temperature superconducting (HTS) cables are expected to offer innovative solutions to these technical bottlenecks. They have therefore been identified as a key technology for the development of next-generation power transmission grids, and a number of development and demonstration projects are currently underway around the world.

Sumitomo Electric Industries, Ltd. has been pursuing the development of HTS wires from the time that HTS materials were first discovered in 1986, and by using HTS wires, it has been working to develop "3-in-One" HTS cables since 1991 [2], [3]. Sumitomo Electric became the first in the world to succeed in electricity transmission on a live grid with these cables in the Albany Project in the United States in 2006 [4]. Since that time, this long-term demonstration has progressed satisfactorily, unattended for a total of nearly nine months of electricity transmission [5].

In the United States, several HTS cable demonstration projects have been conducted in actual power grids; however, no in-grid demonstration is conducted in Japan's power grids. Because of this, in 2007, the New Energy and Industrial Technology Development Organization (NEDO) commenced the High-temperature Superconducting Cable Demonstration Project, the first operation of HTS cables in a live grid in Japan. Sumitomo Electric has been participating in this project to demonstrate the reliability of HTS cable systems in Japan's power system.

This paper describes the development status of HTS cables in this project and the results of verification conducted prior to the demonstration.

2. Development Targets

We aim to introduce HTS cables to the trunk transmission power grid, which currently consists of 275-kV underground cables. At present, replacing the obsolete 275-kV POF cables with CV cables is under consideration. Because CV cables' transmission capacity is lower than that of POF cables, it is necessary to increase the number of circuits if CV cables are used. Unfortunately, the high concentration of public infrastructure in the underground space of Tokyo makes it extremely difficult to construct new cable tunnels. However, if high-capacity, compact HTS cables are used, construction costs could be significantly reduced, as a power capacity equivalent to that of conventional 275-kV cables can be achieved if 66-kV HTS cables are installed within the existing underground conduits with an inner diameter of 150 mm.

If conventional cables are used to construct a 1,000 MVA-class transmission route, three circuits of nine 275-kV single-core CV cables will be required, which will incur a transmission loss of 100 W/m/cct. Three circuits of three 66-kV "3-in-One" HTS cables, however, with an alternating current loss of 1 W/m/ph@3kA, heat invasion of 1 W/m, and cooling system efficiency of 0.1, can reduce transmission loss to less than half that amount at (1x3+1)/0.1 = 40 W/m/cct.

In actual power grids, an inflow of current higher than the normal rated power (fault current) can occur. Due to the large transient current that can accompany a short circuit accident, the maximum fault current condition is set at 31.5 kA, 2 sec for 66 kV-class systems. For HTS cables to be used in practical applications, their soundness must be maintained in the event of such a fault current. Shown in **Table 1** are our development targets for HTS cables, which take these considerations into account.

Table 1. Targets of HTS cable for practical use

Items	Target	Initial status (FY 2007)
Capacity	66 kV / 3 kA	66 kV / 1 kA
AC loss	1 W/m/ph@3kA	0.7 W/m/ph@1kA
Fault current condition	31.5 kA, 2 sec	23 kA, 0.67 sec
AC loss	1 W/m	2.5 W/m
Outer diameter	150 mm conduit	150 mm conduit
Cooling efficiency	0.1	0.06

3. Summary of the High-Temperature Superconducting Cable Demonstration Project

To enable the practical use of HTS cables, it is necessary to meet the technical challenges described above and conduct demonstrations in actual power grids. For this reason, Sumitomo Electric has taken part in NEDO's High-temperature Superconducting Cable Demonstration Project, which began in 2007. An HTS cable system will be built at Tokyo Electric Power Company's (TEPCO's) Asahi substation (Yokohama, Kanagawa) to conduct the first in-grid operation of such a system in Japan, with the objective of demonstrating the reliability of a total system, including construction, operation, and maintenance of power grids, as well as the HTS cables themselves.

In more concrete terms, Sumitomo Electric aims to develop 66-kV-, 200-MVA-class HTS cable systems for use as future transmission systems and verify that they meet all performance and functional requirements for actual power grids by way of sample tests and verification systems. Then, a "3-in-One" HTS cable with a cable-to-cable joint, along with auxiliary facilities such as a cooling system and protective equipment, will be connected to an actual power grid for long-term interconnection tests.

(1) System specifications / configuration

The rated voltage, current, and capacity of the Asahi substation, where the demonstration will be conducted, are

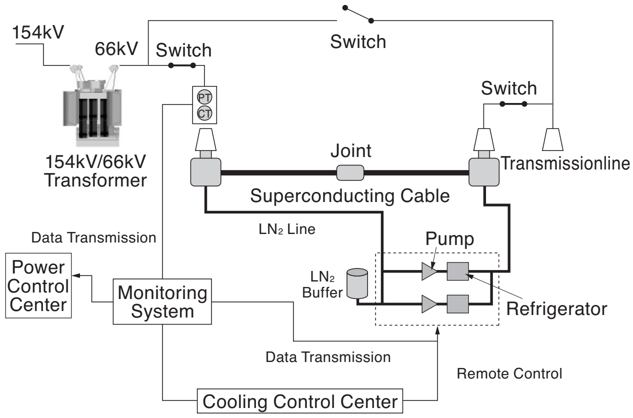

Fig. 1. Configuration of the demonstration system in Asahi substation

66 kV, 1.75 kA (2.25 kA, in the event of overload), and 200 MVA, respectively. Shown in **Fig. 1** is a summary of the cable system, with HTS cables installed through a conduit with an inner diameter of 150 mm and a joint provided in the middle of the cables; both ends of the cables will be connected to power transmission facilities at the substation.

As improvement of the performance of HTS wires is essential to achieve 1 W/m/ph@3kA – the target for practical application, it has been decided to aim for its achievement by fiscal 2012, the final year of the project. Because the rated current of the demonstration grid is 1.75 kA, it has been decided to set the requirement of the HTS cable for the demonstration at the Asahi substation at 1 W/m/ph@2kA. It has been decided, however, that HTS cable be required to allow a current of up to 3 kA, as the cable is subjected to a current of up to 2.25 kA in the event of overload.

When analysis was conducted on the short circuit current that is applied to the HTS cable after an accident in the TEPCO grid, it was discovered that power transmission resumes immediately after the accident location is cut off if the fault current is 10 kA, 2 seconds or shorter. Because of this, the capability to transmit a current rated at 1.75 kV immediately after such an accident (through fault) occurs was also added to the list of requirements. **Table 2** shows the development targets for HTS cables for the demonstration.

Table 2. Targets of HTS cable for Asahi substation

Items	Target
Rated voltage and current	66 kV, 2 kA
Maximum current	3 kA
AC loss	1 W/m/ph@2kA
Fault current condition	Maximum fault current: 31.5 kA, 2 sec Maximum through fault: 10 kA, 2 sec
Outer diameter	150 mm conduit

(2) Project members

Commissioned by NEDO, Sumitomo Electric has been involved in the development of this project together with TEPCO and Mayekawa Mfg. Co., Ltd. TEPCO provides the grid for the demonstration and verifies system operation and maintenance techniques, Mayekawa designs and manufactures the cooling system, and Sumitomo Electric is responsible for the development, manufacturing, construction, and operation of the HTS cable system.

(3) Project schedule

Table 3 shows the schedule for the project. During the first two years, we developed technologies for all elements of the HTS cable system, including those to provide lower transmission losses and withstand short circuit currents. In the third year, a 30-m cable system was constructed and assessed to verify that it meets the required specifications. Finally, a demonstration cable system will be manufactured, which will then be installed at the Asahi substation to conduct long-term verification tests by connecting it to actual power grids.

Table 3. Schedule of Yokohama project

	FY2007	FY2008	FY2009	FY2010	FY2011	FY2012
Cablesystem development	Design: Cable, Joint, Termination; Preliminary tests: AC loss, Fault current test, Mechanical test, etc.		Pre-performance testwith 30m system			
Field test	Analysis of the grid condition		Cable manufacturing; Coolingsystem manufacturing		Install	Long term test

4. Development of Element Technologies for the HTS Cable System

4-1 Development of HTS cables

Photo 1 shows the structure of the "3-in-One" HTS cable. Containing three cores in one thermal insulation pipe (cryostat), this cable offers the advantages of reduced installation space and heat invasion compared with three single-core HTS cables, each requiring a separate cryostat.

A cable core consists of a former made of stranded copper wire and the HTS conductor layer, an insulation layer, the HTS shield layer, and a copper shield layer, all of which are coaxially wound around the former. In the steady-state, a transmitted current flows through the HTS conductor layer. By short-circuiting the shield layer of the three-core cable at both ends, electromagnetic induction makes it possible to pass a current through in the HTS shield layer that is nearly identical to the conductor current and opposite in phase. This structure of the cable provides magnetic shielding, thus preventing electromagnetic interference (EMI) outside the cable. It is not economically practical to design the cable to allow a large current several dozen times larger than the rated current through the HTS conductor wire alone when a short circuit accident occurs. Therefore, by adding a copper former and a copper shield layer to the HTS conductor layer and HTS shield layer, respectively, any fault current is separately diverted to these protective layers so that the resulting temperature rise may be controlled.

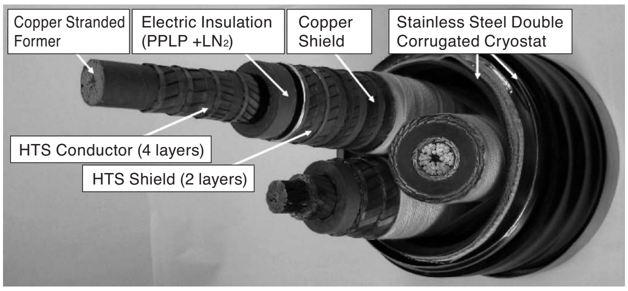

Photo 1. Structure of "3-in-One" HTS cable

High heat-insulation performance is achieved by providing multi-layer thermal insulation between the double-wall stainless-steel corrugated pipes, which contain cable cores, and by maintaining a high vacuum in the space between the two pipe walls. Results obtained from the evaluation of long-term vacuum performance of a 350 m-class cable cryostat [(6)] indicate that this structure can maintain the required level of vacuum for low heat transfer for 100,000 hours or longer after evacuation. Therefore, the cable cryostat was evacuated and sealed at the factory with the appropriate vacuum.

(1) Large current, low AC current loss

Calculations show that the AC current loss of an HTS cable using "DI-BSCCO" Type HT wires (Sumitomo Electric's standard wire) is 2 W/m/ph@2kA. In order to achieve the target of 1 W/m/ph@2kA, it was vital to develop HTS wires with significantly lower loss, so a type of wire with lower AC loss ("DI-BSCCO" Type ACT) was adopted for the HTS cable wire. As shown in **Photo 2**, Type ACT wires contain twisted superconducting filaments, thus successfully reducing AC loss in the parallel magnetic field by one thirds at the wire level.

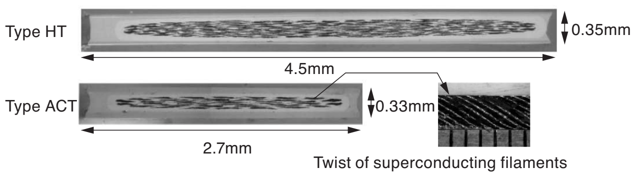

Photo 2. DI-BSCCO (Type HT and Type ACT)

Meanwhile, for an HTS cable using Type ACT wires only, it was necessary to improve the wires' critical current (Ic) characteristic to accommodate large currents. Thus, a hybrid HTS cable was designed that uses both Type ACT wires and Type HT wires in the right placement.

Moreover, in order to reduce the copper former's eddy-current loss to 0.1 W/m/ph@3kA or less, a low-loss type former using a ø0.8 mm element insulating copper wire was developed.

Evaluation of AC loss characteristics of an HTS cable using the low-loss type former and both Type ACT and Type HT wires thus developed revealed that, as shown in **Fig. 2**, AC loss was 0.8 W/m/ph when a 2 kA current was applied, thereby meeting the required specification of 1 W/m/ph or lower. Furthermore, the hybrid design that combined high-Ic Type HT wires also led to success in accommodating the required large current of 3 kA.

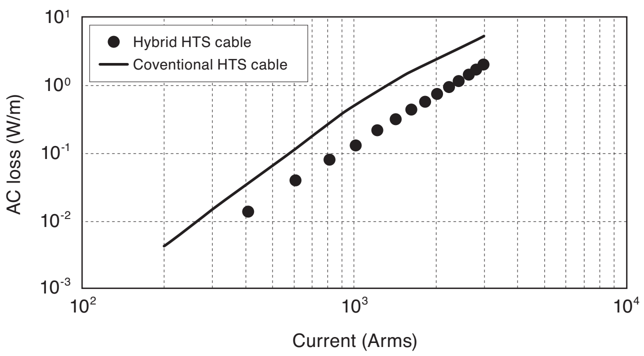

Fig. 2. AC loss test results for hybrid HTS cable core

(2) Withstanding short circuit current

Because it is necessary to limit the temperature increase associated with a short circuit current to a value small enough to avoid impairing the function of the HTS cable, a simulation study was performed to optimize the design of the copper protective layers, taking into account the required size restriction. Based on the simulation findings, a copper stranded former of 140 mm^2 was adopted, and a copper shield layer with a total cross-sectional area of 80 mm^2 was added.

Using this design, a test sample was prepared to conduct a short-circuit test (max. 31.5 kA, 2 sec), which showed that the temperature rise (ΔT) for the HTS conductor layer and HTS shield were 120 K and 110 K, respectively, with both falling within the expected range of simulation results (**Fig. 3**). Furthermore, no deterioration in the critical current characteristics was observed in the test sample after the test, indicating that the sample possesses the required over-current withstanding characteristics.

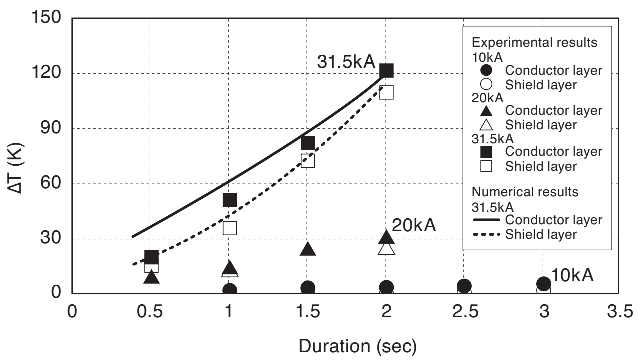

Fig. 3. Fault current test results of HTS cable core

In a test simulated through fault accidents, it was confirmed that the rated current of 1.75 kA and ground voltage of 38 kV were withstood immediately after short circuit current of 10 kA, 2 sec had passed. It was thus concluded that the cable has the characteristics necessary for the power grid at the Asahi substation, where the demonstrations will be conducted.

(3) Electrical insulation characteristics

Earlier HTS cables used polypropylene laminated paper ("PPLP") impregnated with liquid nitrogen as an electrical insulation layer. This structure has worked well in many voltage impression tests, exhibited good heat cycle (cooling and heating) characteristics, and boasts a very small dielectric loss at low temperature. Because of this track record, "PPLP" was adopted as the insulation layer for the cable cores in this project.

In order to verify the electrical insulation performance, a model cable with an insulating layer of 6 mm^t was prepared to conduct a voltage impression test in conformity with JEC-3401. As shown in **Table 4**, test results were favorable across the board, verifying that the required specifications are satisfied.

Table 4. Withstand voltage test results

Items	Required specifications	Test results
AC	AC 90 kV / 3 h	good (no PD)
Imp	±385 kV / 3 times	good

(4) Thermo-mechanical properties

When cooled from room temperature to the liquid nitrogen temperature of approx. -200°C, cables suffer thermal shrinkage of about 0.3%. In previous cable structures, thermal shrinkage while cooling was absorbed by giving the three cores slack. This project, however, aims to develop a cable which has large capacity, withstands short circuit current, and can be installed through conduits of ø150 mm, and so it is essential that resultant cables be compact. However, a design study revealed that the conventional structure with the three cores loosely stranded makes it difficult to use the cable in conduits of ø150 mm. It was thus decided to design a cable with the three cores not loosened.

When cables are cooled from room temperature without any initial slack in the three cores and with both ends fixed, tension is applied to the cable cores due to thermal shrinkage. When the cables are then heated from the cooled state back to room temperature, compressive force occurs as the cables are extended. Measurements of such tensile and compressive forces using a model cable showed that approximately 3 t of tensile force occurred while cooling, and approximately 0.5 t of compressive force occurred as the cores slackened when the temperature rose. It was also confirmed that the cable cores were not damaged by these stresses. Based on these findings, it was decided to use a structure in which the three cores are not loosened to absorb thermal shrinkage for this project.

4-2 Development of cable-to-cable joints and terminations

An indispensable part of long cable systems, the cable-to-cable joints needed to form a power transmission line normally connect cables in underground vaults. Terminations form connections between HTS cables and actual power grids, or form a connection thermally between the liquid nitrogen temperature section and the ordinary temperature section. Shown in **Table 5** are the specifications required at the Asahi substation and those required of 66 kV-class joints and terminations in conformity with JEC-3401.

Table 5. Required specifications for joint and termination

Items	Joint	Termination
Mechanical force	Tensile : 3000 kgf / 3 cores Compression : 500 kgf / 3 cores	
Maximum current	3 kA (continuous current)	
Fault current condition	Maximum fault current : 31.5 kA, 2 sec Maximum through fault : 10 kA, 2 sec	
Joint resistance	< 1 μΩ/joint@3kA	–
Withstanding voltage	AC : 90 kV / 3 h Imp : ±385 kV / 3 times DC : 152 kV / 10 min	
Maximum pressure	0.6 MPa · G	
Earthquake-proof	–	Horizontal : 0.3 G Vertical : 0.15 G
Water-proof	Equivalent to conventional cable	–

(1) HTS joint assembling

Figure 4 is a schematic drawing of the joint. In order to assemble joints in the standard underground vault for 66-kV-class underground cables (approx. 7 m), a space-efficient "3-in-One" structure was adopted. As with conventional cables, a former is connected by using a copper sleeve and the HTS conductor is connected electrically by soldering. Electrically insulation paper is wound around the HTS conductor layer, and the HTS shield is connected with solder as with the HTS conductor. Braided copper wires are used to form press-in contacts for the copper shield layer, which is then finished by winding a protective layer around it. After each of the three cable cores is connected, a nitrogen tank and vacuum tank are assembled. The cable cores are not fixed onto the vessel, but are given room to move to accommodate thermal shrinkage of the cable.

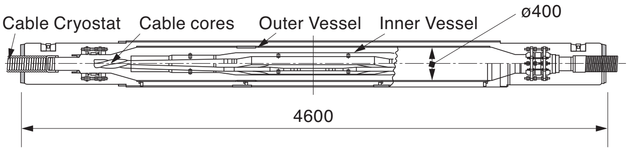

Fig. 4. Schematic view of "3-in-One" HTS joint

A model sample of the joint was prepared with which to verify that the connection resistance of the HTS joint was 6.7 nΩ/phase@3kA and that of the shield joint was 2.5 nΩ/phase@3kA, thus confirming that the target value of 1 μΩ/phase@3kA was achieved. With other tests also producing positive results, it was confirmed that the structure designed for this project meets the required specifications shown in **Table 5**.

(2) Termination assembling

Shown in **Fig. 5** is a schematic drawing of the termination, which was in a "3-in-One" terminal structure where treated terminals of the three cable cores and a three-phase bushing were placed in the same vessel. Each cable core was connected to the copper conductor connector, which was then anchored to the vessel by using a jig made of FRP pipes to deal with the tensile force caused by the cable's thermal shrinkage. A current was supplied to the normally conducting equipment by leading the current to the normal temperature section via the current lead in the bushing. To allow an inducted current, the shield layer was given three-phase short circuit treatment. After the assembly work, the termination vessels were securely attached to the ground.

A model sample of the termination was also prepared to undergo various tests, which subsequently confirmed that the structure designed for this project meets the required specifications shown in **Table 5**.

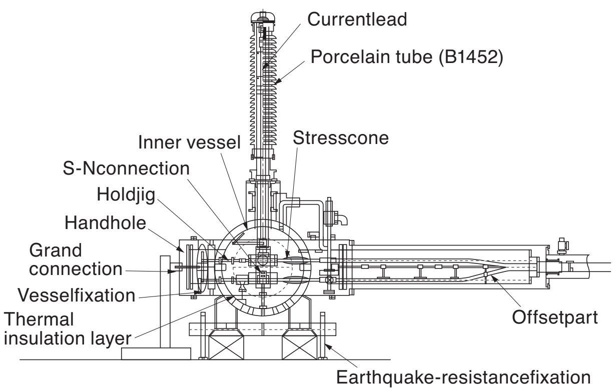

Fig. 5. Schematic view of "3-in-One" HTS termination

5. 30-m Cable System Verifications

For each component of the system, i.e., HTS cables, joints, and terminations, design studies and element tests were conducted to confirm that they all satisfied the required specifications. Then, in order to conduct various tests to evaluate and verify the characteristics of a cable system in its final form, the cable and each piece of equipment were combined and a 30 m-long cable system was built for verification purposes.

5-1 Cable manufacturing/shipment tests

Table 6 shows the specifications for the verification cable, which were determined based on the results of element tests. The cable core was placed in a hybrid structure of four HTS conductor layers and two shield layers, which combined Type HT wires and Type ACT wires. Two out of the three cores of the cables used HTS wires while the third used a dummy wire, and they were referred to as the HTS cores and dummy core, respectively. An element test confirmed that main insulation using a 6 mmt "PPLP" satisfied the specifications, but after considering the track record from previous long-term tests, a 7-mmt "PPLP" was used as insulation.

Table 7 shows the results of shipment tests after manufacturing of the 30-m cable was completed. The tests verified that this cable performed as designed, satisfying the specifications.

Table 6. Specifications of HTS cable for Asahi substation

Items	Specifications
Former	Stranded copper wires with insulation (140 mm²)
HTS conductor	4 layers : Type HT, Type ACT
Electrical insulation	PPLP (thickness : 7 mm)
HTS Shield	2 layers : Type HT
Copper Shield	3 layers : 80 mm²
3-core stranding	Tight 3-core stranding
Thermal insulation (Cable cryostat)	Double-corrugated stainless steel pipe & multilayer vacuum insulation
Sheath covering	PVC

Table 7. Results of cable shipping tests

Test items	Test conditions and design values	Test results
Critical current measurement (Conductor / Shield)	Design value: 6 kA/7 kA	Same as design value (6.1 kA / 7.1 kA)
AC loss measurement	Design value: 0.8 W/m/ph (at 2 kA, 50 Hz)	Same as design value (0.8 W/m/ph)
Bending test	18D (D = cable outer diameter)	No Ic degradation No defect in HTS tapes and electrical insulations
Withstanding voltage test	AC : 90 kV / 3 h Imp : ±385 kV / 3 times	Good
Construction test	Dismantling inspection for cable	Same structure and size as design

5-2 System construction

Figure 6 shows the configuration of the verification system. The cable is approximately 30 m long, with a ninety-degree bend 5 m in radius, terminations at both ends (terminations A and B), and a cable-to-cable joint in-between. The cable system was operated by combining it with a cooling system to circulate liquid nitrogen. The cooling system mainly consisted of two 1 kW-class refrigerators, a liquid nitrogen circulating pump, and a reservoir tank.

(1) Assembling of HTS joints and terminations

After the cable installation was completed, HTS joints

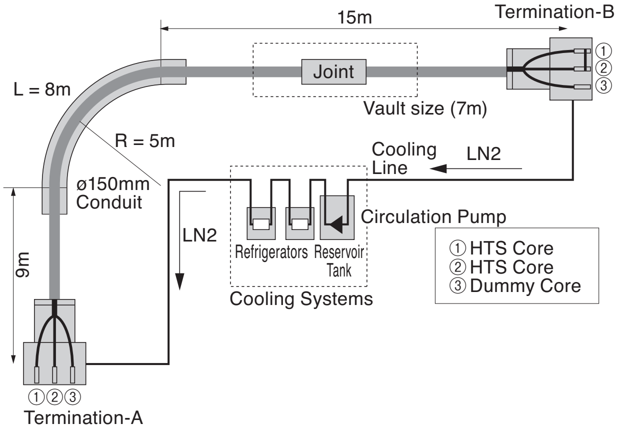

Fig. 6. 30-meter HTS cable system configuration

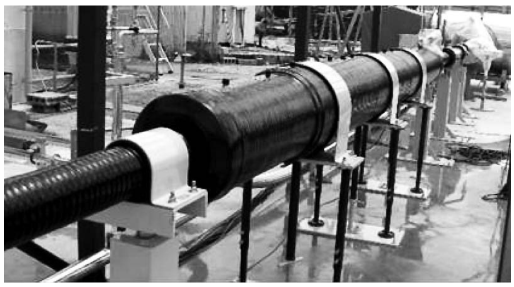

Photo 3. "3-in-One" HTS joint

Photo 4. "3-in-One" HTS termination

and terminations were assembled. HTS joints were assembled in a space that simulated a 7-m-long vault, dimensions that were included in the development targets. **Photo 3** shows an assembled HTS cable-to-cable joint. HTS terminations after assembly and a complete view of the verification system are shown in **Photos 4 and 5**.

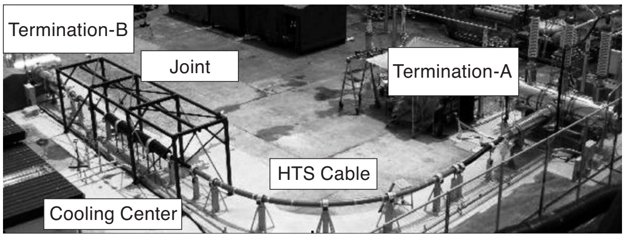

Photo 5. Completed 30-meter HTS cable system

(2) Cooling system

The cooling method adopted for the verification cooling system is a direct cooling method in which the same liquid nitrogen passes through both the refrigerator side and the HTS cable side, sending liquid nitrogen cooled by the refrigerator directly to the HTS cable system. **Table 8** shows the specifications of the cooling system, and **Photo 6** shows the cooling system.

(3) Measuring system

The measuring system monitored the HTS cable system in operation, checking parameters such as the temperature, pressure, and flow rate of each part, so that a warning could be issued without delay if any abnormality was found. Its surveillance function was networkable, so as to enable remote data monitoring and a warning function.

Table 8. Cooling system specifications

Items	Specifications
Operating temperature	66 – 77 K
Operating pressure	0.2 – 0.5 MPa · G
Flow rate	Max. 40 L/min
Cooling capacity	2 kW@77K, 1.6 kW@67K
Regulation	Japanese high pressure gas safety law

Photo 6. Cooling system

5-3 Verification tests (Phase I)

The 30-m-long verification system was cooled and is currently being subjected to various tests, including electrical tests, mechanical tests, and heat loss measurement. Shown in **Table 9** are the specifications of the verification tests. As of this writing (September 30, 2009), Phase I of the rating validation test has just been completed. This section reports its results.

Table 9. 30-meter HTS cable system test schedule

Tesitems	Schedule	Detailed test items	
1st Cool Initial Test	July-Sep, 2009	Electrical Test	Critical current measurement Shieding current measurement Electrical insulation tests Rated load test (40kV to the grand, 2kArms)
		Thermo-mechanical Test	Tension produced during initial cooling Movement of the core -to core joints by X -ray
		Thermal Test	Heat loss measurement on no load condition AC loss measurement (2kArms)
		Long-term operation Test	AC 51kV to the grand : continuous 2kArms loding : 8 hours -ON/16 hours-OFF
2st Cool Heat-cycle Test	Sep-Oct, 2009	To Confirm the cable properties after heat-cycles by electrical, thermo mechanical and thermal tests.	
3st Cool Tolerance Confimation Test	Nov, 2009-Jan, 2010	To Confirm the cable properties after heat-cycles by electrical, thermo mechanical and thermal tests. Over-current test (~3kArms) Fault-current test (~10kArms) Trial examination for the troubles of cooling system	

(1) Initial cooling

The initial cooling of the HTS cable system was conducted by controlling the temperature in the lengthwise direction of the cable, the cable's tensile force, etc. **Figure 7** shows the temperature profile of the initial cooling process as measured using optical fiber in the cable. Cooling was first conducted at the cable's termination A. In order to control rapid behaviors due to temperature change during the cooling process, the cable was cooled gradually over its entire length using nitrogen gas at a temperature of -100°C, and then the temperature of the nitrogen gas being fed into the cable was gradually lowered. When the temperature at the inlet of the cable reached -120°C and the temperature gradient along the entire length of the cable had become sufficiently low, liquid nitrogen was then injected into the cable until the entire length of the cable was cooled to the temperature of liquid nitrogen (-200°C). The initial cooling process took approximately 45 hours to complete.

During the initial cooling process, the maximum tensile force produced at both terminations was a total of approximately 2500 kgf for the three cores, which was almost equivalent to the value estimated from tension produced during the element test cooling process.

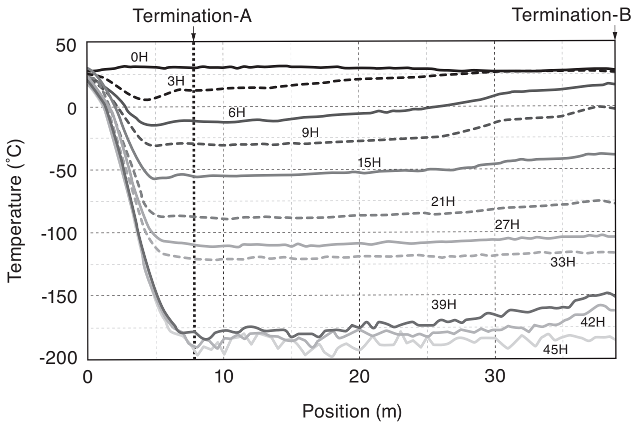

Fig. 7. Temperature profiles of 1st step initial cooling

(2) Critical current measurement

After the initial cooling process was completed, critical current (I_c) measurement was conducted for the entire length in order to verify the soundness of the conductor. I_c measurement was performed by applying go-and-return current to the conductor with two HTS cores. Shown in **Fig. 8** are the I_c measurements for the conductor with the cable outlet temperature at 77.4 K. I_c was measured at 5.4 kA (1 μV/cm criterion), and agreed well with the values that were estimated from the results of the shipment test (6.1 kA) and the I_c's lowering rate due to the magnetic field produced when go-and-return current is applied to a conductor with two cores. These results confirmed that the conductor was free from any abnormality or deterioration that might have occurred during the processes of cable manufacturing, transportation, on-site installation, assembly, and cooling.

(3) Alternating current application test

In order to verify the soundness of the HTS shield, an alternating current of 2 kA was applied to the HTS layer and the current that was induced to the shield layer was measured. As shown in **Fig. 9**, a current in reverse phase from the conducting current flow was induced through the HTS shield layer (induction rate: approx. 92%). This result is similar to previous measurements, thus confirming that the HTS shield has no major abnormalities.

(4) Withstand voltage test

The final test was the withstand voltage test required for 66-kV-class power cables. A commissioning withstand voltage test for the demonstration test on-site system (AC76 kV, 10 minutes) and a voltage test corresponding to the system's maximum voltage (AC42 kV, 8 hours) produced favorable results, thus verifying the soundness of the verification 30-m cable.

(5) Long-term electric current application test

In order to verify whether the HTS cable system is capable of handling the rated current and voltage for thirty years, a long-term operation test was performed. During a period of thirty days, ground voltage of 51 kV was continuously applied as an accelerated test condition to simulate thirty years of operation, while at the same time a current application cycle test was conducted (rated current of 2 kA was applied for 8 hours and then turned off for 16 hours). The operating conditions for the cooling system were: minimum pressure at the cable of 0.2 MPaG, cable outlet temperature of approx. 77 K, and liquid nitrogen flow rate of 40 L/min.

During the test, no major change was observed in the temperature of the cable or other sections, and the 30-day long-term operation test was completed successfully. The test results are shown in **Fig. 10**. Phase I of the project was completed with no detected partial discharge pulse during the measurement taken after the long-term current application test.

In Phase II and Phase III, heat cycle and marginal performance will be tested.

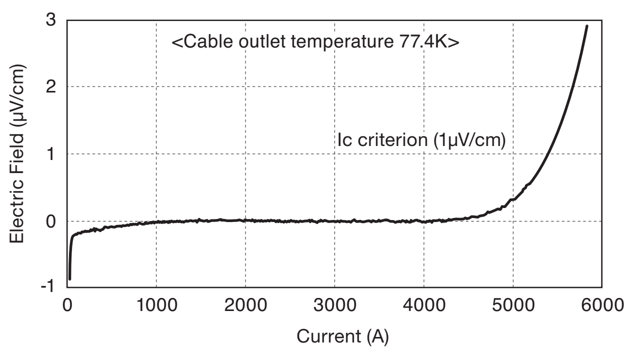

Fig. 8. Analyzed I-E characteristics of cable conductor

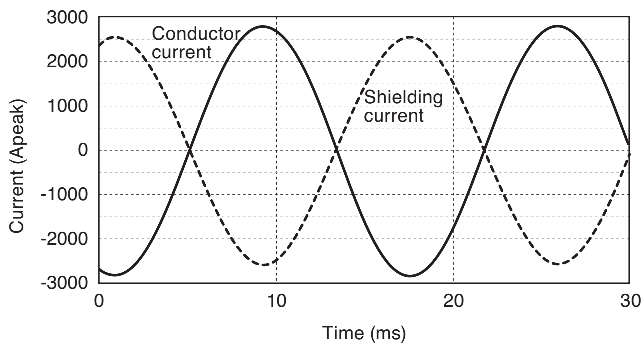

Fig. 9. Waveform of HTS shielding current at loading current of 2 kArms

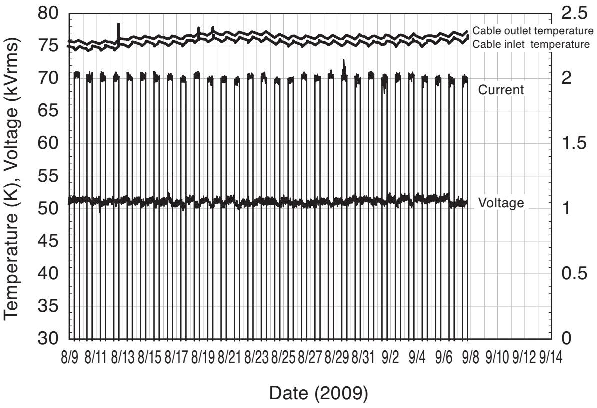

Fig. 10. Status of long-term operation test in 1st cool

6. Conclusions

With a view towards accelerating the practical application of HTS cables, an innovative technology that is expected to offer solutions to global warming and achieve the replacement of obsolete power cables with larger capacity ones, Sumitomo Electric is currently involved in Japan's first project to demonstrate the performance of such cables in live grids. So far, Sumitomo Electric has been involved in the technological development of some of the key elements of HTS cables that are applicable to actual power grids (cables, cable-to-cable joints and terminations, cooling system, etc.), and is verifying their performance in a cable system, the final form of these technologies. Going forward, Sumitomo Electric will conduct long-term interconnection tests by connecting the system to actual power grids, so as to demonstrate the reliability and stability of the HTS cable system, while at the same time identifying any challenges involved in its practical application by studying the ways in which these systems should be operated and maintained in actual power grids.

HTS cable technology is applicable not only in Japan but in other countries as well. In the United States, the "Grid 2030" initiative is being promoted to construct a strong trunk transmission system for the sake of energy security as the US transmission system goes obsolete, and HTS cables are expected to play an important role in this project. In China, too, demand is growing for more power transmission lines in tandem with the rapid development of their domestic economy. All in all, demand for HTS cables outside of Japan is expected to be several dozen to several hundred times greater than within Japan. Above all, reducing CO_2 emissions is one of the most pressing global environmental issues that must be addressed if we are to create a sustainable society. Recognizing that the commercialization of HTS cables, which are seen as a potential solution to this issue, is one of the key tasks for Sumitomo Electric, which has long been working to underpin social infrastructures, we are determined to make further efforts to realize the practical application of this technology at the earliest possible date.

* 3-in-One, DI-BSCCO and PPLP are trademarks or registered trademarks of Sumitomo Electric Industries, Ltd.

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